APPARATUS AND METHOD FOR PROGRAMMABLE CONTROL OF LASER DIODE MODULATION AND OPERATING POINT

RELATED APPLICATIONS

This application is related to U.S. provisional application 60/204,316 filed May 17, 2000 and from which it claims benefits under 35 U.S.C. §119(e).

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to semiconductor laser control, and more specifically to an apparatus and method for programmable control of laser diode modulation and operating point.

2. Background of the Invention

Laser diodes and laser diode modules are increasingly used in computer and telecommunications networks, due to their low

cost and wide bandwidth potential. In particular, laser diodes are used in applications such as Dense Wave Division Multiplexing (DWDM) systems. DWDM systems use laser diode outputs at multiple wavelengths. The outputs are combined and introduced into a single optical fiber to achieve data rates higher than possible with an optical connection with a single source and detector.

In order to manufacture optical transceivers at low cost and high volumes, it is desirable to produce a complete integrated circuit solution for controlling a laser diode for use in constructing a complete transceiver circuit. A complete integrated solution has not been practical, due to the variations between individual laser diodes from a single manufacturer and differences between laser diode designs from different manufacturers. Additionally, laser diodes in common use include a monitor photodiode optically coupled to the laser diode. The optical coupling of the monitor diode to the laser diode is also variable, compounding the difficulties of manufacturing a complete integrated circuit solution.

The efficiency of the laser diode and the operating point and transition times of the laser diodes vary widely, causing systems manufacturers to incorporate tuning circuits in their systems that must be adjusted after assembly of the control circuit and the laser. The resources required to tune each of the laser diode assemblies increases the cost of production and reduces the volume of components that may be produced.

Circuits incorporating electrical alterable memories have been implemented that control the bias current of the laser diode, but this is not a complete solution to the problem. Due to the variations in efficiency between laser diodes and variations in transition time for the signals transmitted by the system must be compensated via tuning.

Additionally, due to the wide variations in efficiency, a circuit designed for a low efficiency laser diode may drive a high efficiency diode at too high an AC amplitude, causing the high efficiency diode to fall out of lasing mode and entering the light-emitting diode (LED) region of operation. If the A/C modulating signal amplitude is so high as to cause the laser

diode to leave the lasing mode, data communications will be completely disrupted, as the data signal is a high-frequency intensity modulation superimposed on the operating point intensity of the laser. When the laser diode falls into LED mode, the intensity drops dramatically. The loss in intensity will cause a detector that is detecting the modulation to experience a total loss of signal.

Finally, operation of the laser diode must be controlled in a manner that is stable over temperature variations, has startup characteristics that will not damage the laser diode, and will not harm personnel that may be exposed to the light emitted from the laser diode. IEEE standard 802.3 sets forth guidelines for operation of laser diode communications modules and limits on output intensity for safety of personnel.

Therefore, it would be desirable to provide a method and apparatus for programmable control of laser diode modulation swing and transition time as well as laser diode operating point to accommodate a wide variety of laser diodes from various manufacturers using a single integrated circuit component

design. It would further be desirable to provide a method and apparatus that control laser diode operating point that is temperature compensated and limits the minimum and maximum output of the laser diode.

SUMMARY OF THE INVENTION

The above objective of programmably controlling laser diode modulation and operating point are achieved in an apparatus and method. The apparatus and method may set a limit control on an amplifier in the modulation signal path as well as a coupling capacitance that affects the transition times of the modulation signal as applied to the laser diode. The limit control and coupling capacitance are set by values retrieved from a memory. Additionally, a bias circuit providing a precision voltage reference and thermal compensation may be employed to provide stable control of laser diode operating point. The voltage reference may be controlled by an under-voltage lockout circuit and power-on reset circuit and supplied to an external pin of an integrated circuit in order to provide reference and control functions from a single external pin.

The foregoing and other objectives, features, and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiment of the invention, as illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a graph depicting operational characteristics of a laser diode drive circuit in accordance with a preferred embodiment of the invention.

Figure 2 is a schematic diagram depicting an integrated circuit coupled to a laser diode in accordance with a preferred embodiment of the present invention.

Figure 3 is a schematic diagram depicting features of the bias control circuit of **Figure 1.**

Figure 4 is a schematic diagram depicting the R2R resistor array **16** of **Figure 2.**

Figure 5 is a schematic diagram depicting the C2C capacitor array **14** of **Figure 2.**

Figure 6 is a schematic diagram depicting the I2I current source **13** of **Figure 2.**

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

With reference now to the Figures, and in particular with reference to **Figure 1**, operational characteristics in accordance with a preferred embodiment of the invention are depicted. A laser diode produces an optical output in response to a drive current that is passed through the laser diode. As depicted in **Figure 1**, there are two regions of operation that are of interest: LED mode and Laser Mode. At current levels below the laser threshold, the optical output of the laser diode is low, similar to a light-emitting diode (LED). Above the laser threshold current, the laser diode begins to lase, producing substantially greater optical output power as the laser diode drive current is increased up to the maximum operating current of the laser diode.

The drive circuit of the present invention is adapted to provide a DC operating point and a modulation swing such that the minimum level of drive current passed through a laser diode is above the laser threshold and the maximum laser output is

below a maximum level of brightness. Laser diodes available from various manufacturers have different characteristics. The laser threshold differs, as well as the maximum operating current. In order to manufacture a single integrated circuit solution, the DC operating point and modulation signal swing must be carefully controlled so that the minimum value of the laser diode drive current does not drop below the laser threshold and the maximum value of laser diode drive current does not exceed the maximum operating current. The rate of change of optical output power with respect to laser diode drive current also differs for different manufacturer's laser diode, making it necessary to adjust the modulation swing to accomplish a given modulation index. Laser intensity levels for binary modulation signals producing a digital "1" and "0" representation corresponding to maximum and minimum brightness levels are set by industry standards such as IEEE 802.3, promulgated by the Institute of Electrical and Electronics Engineers (IEEE). Rise and fall times of the modulation signal must also be controlled in accordance with industry standards.

Additionally, laser diodes from the same manufacturer may

have substantial variations from device to device and with ambient temperature of the laser diode. Therefore, a mechanism for controlling the DC operating point and modulation swing must be integrated within a controller that is flexible enough to interface a variety of laser diodes under all conditions. Since operating limits for the laser must be maintained both for the protection of the laser, and to ensure that personnel are not exposed to laser light above a predetermined intensity, mechanisms that control the DC operating point to set a maximum intensity and to control the intensity under abnormal operating conditions are necessary within an integrated circuit controller that will operate across the variation of laser diodes supported.

Referring now to **Figure 2**, an integrated circuit **10** coupled to a laser diode **D2** in accordance with a preferred embodiment of the invention is depicted. Laser diode **D2** is optically coupled to a monitor diode **D1**, which provides an output that is proportional to the intensity output of laser diode **D2**, thereby providing a laser intensity detector. A feedback mechanism comprising voltage controlled current source (VCCS) **15**, current

mirror **M1**, resistor array **16**, amplifier **A1**, buffer **A2**, and control transistor **N1** (that is coupled to amplifier **A1** by resistor **R2**) uses the output of monitor diode **D1** to generate a controlled bias current through laser diode **D2**. Capacitor **C1** is low ESR capacitor for shunting the high-frequency modulation signal from monitor diode **D1**.

Monitor diode **D1** is biased through resistor **R1** by a voltage reference output **Uref** that is also common to circuits within laser diode controller **10**. This permits rejection of power supply noise and ripple voltage variations to which typical laser diode controllers are susceptible. The reference output pin supplying the monitor diode bias voltage may be used for other purposes outside an integrated circuit implementing laser diode controller **10**, such as determining comparator thresholds for such circuits are laser intensity detectors, etc. Resistor **R1** can be a low temperature coefficient type, permitting a stable bias current and can be used to scale the feedback loop that controls laser diode **D2** operating point, since voltage across resistor **R1** produced by the monitor diode bias current will control the amplitude of the feedback signal to laser diode

controller **10**. Generally, resistor **R1** should be chosen to have no temperature variation or as little temperature variation as possible, so that the circuits internal to laser diode controller **10** may be designed to have no temperature variation.

Voltage controlled current source (VCCS) **15**, detects the voltage across resistor **R1** and converts it to a current that is coupled to current mirror **M1**. Current mirror **M1** then generates a current proportional to the monitor diode **D2** voltage, drawing the current through R2R resistor array **16**. The feedback loop is thermally stable, as resistor **R4** within VCCS **15** determines the current through R2R resistor array **16**. In the preferred embodiment, resistor **R4** is an hpoly or P^+ resistor fabricated in the same sea of resistors as the hpoly or P^+ resistors within R2R resistor array **16**. Therefore error due to temperature variation of resistor **R4** and R2R resistor array **16** is cancelled. Use of a current loop also improves the power supply rejection ratio (PSRR) of the feedback loop and temperature compensates the loop through matching variation in resistor **R4** and variations in R2R resistor array **16**, as does using the **Uref** signal as a reference rather than a power supply rail.

Amplifier **A1** is an operational amplifier that will amplify the difference voltage developed by R2R resistor array **16** produced by current mirror **M1**. The inverting input of amplifier **A1** is coupled to a reference divider formed by resistors **R5** and **R6** via a resistor **R3**. Resistors **R3**, **R5** **R6** and $\mathbf{R_f}$ can be matched so as to cancel thermal variation. The output of amplifier **A1** is buffered by a unity gain buffer **A2** that biases transistor **N1** to control current through laser diode **D2**. The gain and characteristic response of the laser diode bias feedback loop can be adjusted by external resistor $\mathbf{R_f}$ and external capacitor $\mathbf{C_f}$. Resistor $\mathbf{R_f}$ is optional and may be removed entirely, yielding an integrator. Without resistor $\mathbf{R_f}$ operation of the loop will be that of a proportional-integral (PI-control) controller. Otherwise, with resistor $\mathbf{R_f}$ included and optional capacitor $\mathbf{C_f}$ omitted, the loop forms a proportional controller (P-control).

Factory programming of the bias circuit is achieved through a memory **12** that is coupled to R2R resistor array **16**. The resistance value of R2R resistor array **16** determines the bias voltage and is set by loading data from memory **12** into a shift register in R2R resistor array **16**. A memory loading circuit **11**

receives an external **data** and **clock** signal for loading values to control R2R resistor array **16** as well as C2C capacitor array **14** and I2I current source **13**. A decoder may be provided within memory loading circuit **11** that separates a data signal from a clock signal, thus providing a one-wire data loading input that does not require a separate clock signal. The memory loading circuit **11** may also include level-shifting inputs on the **data** and **clock** inputs and a location in memory **12** may be used to select the input signal levels. In this manner, an interface to (emitter coupled logic) ECL or (Transistor-Transitor Logic) TTL may be supported without external circuitry. Once the selection is made by programming memory **12** using default level signals, subsequent interfaces may be made at another logic level, permitting factory customization of the logic levels supported. If fault logic and other logic circuits have outputs provided from laser diode controller **10**, the logic outputs may be level adjusted to conform to the level selection stored within programmable memory **12**.

The values in memory **12** are generally factory programmed by the laser diode/controller system integrator (e.g., the

manufacturer of a transceiver) in order to tune each laser diode **D2** to each laser diode controller **10**. Memory **12** is generally a one-time-programmable memory (OTP), but may be an electrically erasable memory (EEPROM), or a volatile memory loaded from another storage means or algorithm. An OTP memory **12** is generally preferable, as OTP memories are more reliable than electrically erasable memories and failure of the memory value may cause unsafe operation of laser diode **D2**.

Alternatively, an analog electrically erasable memory (analog E^2) may replace memory **12** and R2R resistor array **16**, permitting a stored voltage to directly control amplifier **A1** to produce a stored laser diode bias value. In this alternative embodiment, the output of the analog E^2 memory is coupled to a mosfet and the voltage set to bias the mosfet in the triode region, thus producing a variable resistor that replaces R2R resistor array **16**.

Operation of the laser diode bias circuit is further controlled by an under-voltage lockout circuit **UVLO** and a power-on reset circuit **POR**. **Bandgap** reference provides a stable output

reference voltage for operation of the laser diode controller **10.** The **bandgap** is coupled to the power supply input of the laser diode controller **10** and derives an output free of power supply variation and noise. The output of the **bandgap** is buffered by buffer amplifier **A3** and supplied to an external pin that is used to bias monitor diode **D1**, providing performance superior to prior designs that do not supply a dedicated voltage reference to bias the monitor diode. The prior designs are susceptible to power supply variations and noise and typically use the same power supply that is used to power the bias control circuit. Additionally, the buffered reference output is useful for deriving external references, such as thresholds of comparators that provide external safety measurements.

When the input voltage to the laser diode controller **10** is insufficient for operation, AND gate **AND1** will have a logic low output, disabling buffer amplifier **A3** and removing the **Uref** reference signal from the internal bias circuit. This action will disable amplifiers **A2** and **A3**, turning off transistor **N1**, which in turn deactivates laser diode **D2**. An additional breaker circuit may be added to amplifier **A1** to completely clamp its

output when the **Uref** signal is disabled by buffer **A3** or the logic enable signal may be used to control a clamp coupled to amplifier **A1**. Similarly, during initialization of laser diode controller **10**, power-on reset circuit **POR** will disable buffer amplifier **A3** via AND gate **AND1**. Since the **Uref** signal is output from laser diode controller **10**, external circuitry requiring a power-on reset and undervoltage lockout can use the **Uref** signal to condition operation, eliminating the need for an external circuit to provide these functions. The **Uref** signal combines a reference, power-on reset information and UVLO information in one external pin, making this information available to external circuitry using a minimum of connections.

Control of the modulation swing of laser diode **D2** and control of the rise and fall times of the modulated levels of laser diode **D2** drive current are also provided by laser diode controller **10**. An amplifier **A4** couples a differential modulation signal input to laser diode **D2** via an optional external capacitor $\mathbf{C_{ext}}$ and an internal C2C capacitor array **14**. C2C capacitor array permits tuning of the coupling capacitance to laser diode **D2** by values loaded from memory **12**, which are

generally factory programmed. Thus, control of transition time (rise and fall time) of the modulation applied to laser diode **D2** is accomplished by laser diode controller **10.**

Control of laser diode **D2** modulation swing is accomplished by setting the maximum amplitude swing of the output of amplifier **A4,** which is generally a high frequency Gas (Gallium Arsenide) amplifier. Amplifier **A4** is generally an amplifier having a current output, but the output of amplifier **A4** may be a voltage, which is then converted to a current. Since the modulation input may contain information having a frequency higher than 1 Ghz, amplifier **A4** generally will not be integrated within integrated circuit controller **10.**

The control of the output levels produced by amplifier **A4** is made via a bias input. I2I current source **13** controls the bias level and is coupled to memory **12,** whereby values are loaded to control the maximum amplitude of amplifier **A4** and thereby the modulation swing applied to laser diode **D2.** Since the maximum current output of amplifier **A4** is symmetrical and bipolar, the minimum laser diode current is the quiescent

operating current of diode **D2** as set by the bias control circuit minus the maximum current output of amplifier **A4.** The maximum laser diode current is the quiescent operating current plus the maximum current output of amplifier **A4**. Alternatively, the output of amplifier **A4** may be a unipolar current, or be asymmetrical with respect to a zero output current, but the same principles apply. For example, the output of amplifier **A4** may range from zero current to a positive DC current. In this case, the quiescent current of laser diode **D2** will be the current output from the bias control circuit plus half of the maximum current output of amplifier **A4**. The illustration described above is for an amplifier **A4** that has a current control input. For an amplifier having a voltage control input, the I2I current source **13** output can be converted to a voltage.

Alternatively, an analog electrically erasable memory (analog E^2) may replace memory **12** and I2I current source **13**, permitting a stored voltage to control the modulation swing of amplifier **A4**. In this alternative embodiment, the output of the analog E^2 memory is coupled to a VCCS and the current output used to bias the control input of amplifier **A4**. If analog E^2 is used

to set bias and modulation swing for the laser diode, memory **12** should still include digital memory for the control of C2C capacitor array if it is included within an IC laser diode controller.

Referring now to **Figure 3**, features of the bias circuit of **Figure 2** are depicted. VCCS **15** includes an amplifier **A11** coupled to a p-channel transistor **P11** to produce a current output that is proportional to the voltage across monitor diode **D1** of **Figure 2**. Resistor **R4** is also included within VCCS **15** and is further coupled to reference voltage **Uref**, so that the temperature variation of resistor **R4** will cause a corresponding variation in the current through transistor **P11**. (This variation will in turn be cancelled by a corresponding variation in the voltage produced across R2R resistor array **16** of **Figure 2**). The current drawn through transistor **P11** is coupled to current mirror **M1**.

Current mirror **M1** is an N-channel cascoded supercurrent mirror that maximizes the matching between transistors on a common die. (A bipolar or folded current mirror could also be used.) Transistors **N12** and **N14** form the mirror pair and have

gates coupled to the input terminal of current mirror **M1**. The current introduced into current mirror **M1** is coupled through the channel of transistor **N12** via transistor **N11**, which is biased by amplifier **A10** according to standard cascode techniques. A transistor **N13** that is matched to transistor **N11**, couples the mirrored current through transistor **N14** to current output **Iout**. While transistors **N11** and **N13** are depicted as field-effect transistors, bipolar transistor current mirror transistors and cascodes may also be used.

Referring now to **Figure 4**, details of R2R resistor array **16** of **Figure 2** are depicted. A shift register **32** receives a data and a clock signal whereby values may be loaded from memory **12** of **Figure 1**. Individual bits clocked into shift register **32** control transmission gates **30A - 30C** to short out resistors corresponding to values not needed to form the programmed resistance value. Since the resistors are arranged in a power-of-two sequence within the resistive ladder within R2R resistor array **16**, any value may be programmed up to $R \cdot (2^{(N+1)}-1)$, yielding N bits of resistance resolution. The dashed line connecting

resistors within R2R resistor array depict that the number of resistors used in a controller integrated circuit design may be determined by the resolution required for operation of the bias circuit for the range of laser drive parameters required. Additionally, the resistance values within resistor array **16** may be chosen in increments other than powers-of-two, for example, a greater resolution may be around the lower end of the resistance scale by including more precision near the least significant bit (LSB).

Referring now to **Figure 5**, details of C2C capacitor array **14** of **Figure 2** are depicted. A shift register **42** receives a data and a clock signal whereby values may be loaded from memory **12** of **Figure 2**. Individual bits clocked into shift register **32** control transmission gates **40A - 40C** to couple capacitors corresponding to values needed to form the programmed capacitance value. Since the number of capacitors coupled to the transmission gates **40A - 40C** increased in a power-of-two sequence within C2C capacitor array **14**, any value may be programmed up to $C^{\cdot}(2^{(N+1)}-1)$, yielding N bits of capacitance resolution. The dashed line connecting capacitors within C2C

capacitor array depict that the number of capacitors used in a controller integrated circuit design may be determined by the resolution required for operation of the transition time control circuit within the range of laser drive parameters required. Additionally, the capacitance values within capacitor array **14** may be chosen in increments other than powers-of-two, for example, a greater resolution may be around the lower end of the capacitance scale by including more precision near the least significant bit (LSB).

Referring now to **Figure 6**, details of I2I current source **13** of **Figure 2** are depicted. A shift register **52** receives a data and a clock signal whereby values may be loaded from memory **12** of **Figure 2.** Individual bits clocked into shift register **52** control switches **S50A - S50C** to couple the gates of switch transistors **N51**, **N53**, and **N55** to a bias voltage produced by bias generator **54.** When a switch is deselected, the gate of the associated transistor is coupled to the power supply rail and no current is switched through that transistor, effectively shutting of the current source. Bias generator 54 is a bias generator designed to provide a reference bias voltage to

develop current through transistors **N50**, **N52** and **N54** and to provide a cascode voltage reference which when connected ensures that current sources & cascoded devices are properly in saturation over the entire range of operation. Current source transistors **N50**, **N52**, and **N54** are sized to produce currents corresponding to values increasing in a power-of-two sequence and are coupled to the switch transistors **N51**, **N53**, and **N55** connected in cascode so that when the bit for a particular current source is in the selected state (logic high), the corresponding cascode transistor is connected to its appropriate cascode bias voltage.

Since the values of the current sources coupled to the output within I2I current source **13** are set in powers of two, any value may be programmed up to $I_o \cdot (2^{(N+1)}-1)$, yielding N bits of current resolution. The dashed line connecting current sources within I2I current source capacitor array depict that the number of current sources used in a controller integrated circuit design may be determined by the resolution required for operation of the modulation swing control circuit within the range of laser drive parameters required. Additionally, the

current source values within current source **13** may be chosen in increments other than powers-of-two, for example, a greater resolution may be around the lower end of the bias current scale by including more precision near the least significant bit (LSB).

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing and other changes in form, and details may be made therein without departing from the spirit and scope of the invention.